Microsecond Accuracy at Multiple Locations: Is it possible without GPS?

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For time metrologists, a microsecond (10^{-6} s) is not an especially short interval. The Global Positioning System (GPS) has made it easy to synchronize a clock within nanoseconds (10^{-9} s) [1] and time interval counters with resolutions measured in picoseconds (10^{-12} s) have been common for decades [2]. In more recent years, the femtosecond (10^{-15} s) frequency comb has become a fixture at the most advanced laboratories [3]. Because most research focuses on new advances, the microsecond is almost a forgotten unit in the recent literature about time metrology.

In a practical sense, however, a microsecond is still an interval so short that it nearly defies comprehension. Light in a vacuum only travels about 299.8 m per microsecond, or slightly more than the length of a football field. The “moving” images that we see on television are actually static for many thousands of microseconds. Even when a sporting event appears to be “too close to call”, such as Michael Phelps’s dramatic victory in the 100 meter butterfly at the 2008 Olympics, video recorded at 10,000 frames per second (one frame every 100 microseconds) can easily reveal the winner.

The industrial timing world lies somewhere between the state-of-the-art timing practiced in laboratories, and the modest timing requirements of everyday life. The microsecond is the most discussed unit in industrial timing systems, because microsecond accuracy is required to support critical infrastructure. Most critical infrastructure timing systems depend upon GPS, simply because microsecond accuracy is easy to achieve with GPS, and difficult to achieve without it. This paper explores how GPS clocks meet the accuracy requirements of two critical-infrastructure applications, mobile telephone networks and the electric power grid. Both industries require time accurate to a microsecond [4] at thousands of geographically dispersed locations, and thus rely upon thousands of GPS clocks. The paper also discusses the vulnerabilities of GPS clocks, and reviews possible backup strategies for maintaining microsecond accuracy across a large geographic region when GPS is unavailable.

How GPS Clocks Maintain Microsecond Accuracy

Several established methods for transferring time from one location to another have been described in the literature for many years [5] and are continuously being refined [6, 7]. All time transfer methods have a reference clock at their source (point A). Information from the reference clock is encoded on to a signal that is sent through a wired or wireless medium to its destination (point B), where the remote clock is located (Fig. 1). The remote clock is synchronized using the time from the reference clock, which is corrected to include the path delay through the medium, d_{ab}. Even if the reference clock is a “perfect” source of Coordinated Universal Time (UTC), the accuracy of the time transferred to the remote clock can be no better than the uncertainty of the path delay measurement [8]. This simple fact can be thought of as the first rule of time transfer.

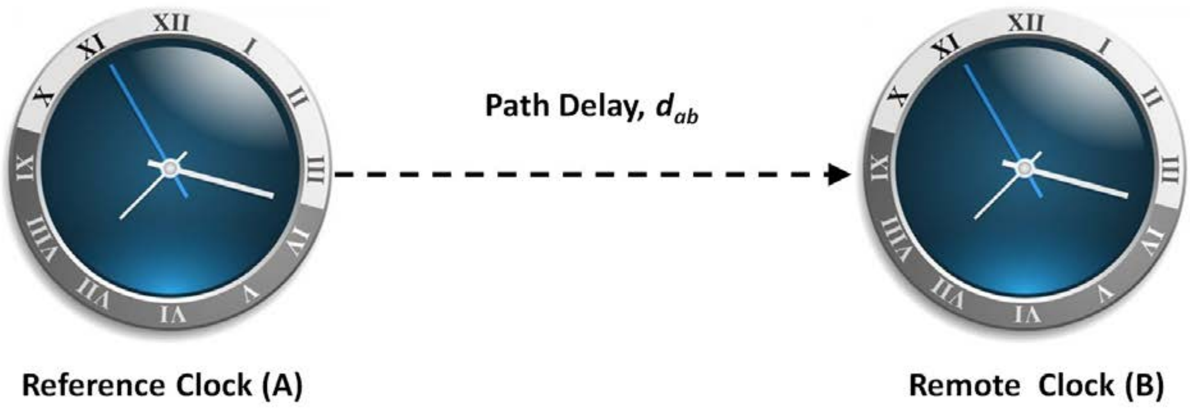

Fig. 1. A one-way time transfer system.

It is difficult to accurately measure the path delay through some mediums. For example, shortwave radio signals were once commonly used to transfer time, but path delay measurements normally had an uncertainty of at least a few hundred microseconds due to variations in the height of the ionosphere and other factors [9]. Network time transfer systems, such as those that utilize the Network Time Protocol (NTP), do a fine job of synchronizing the clocks of computers connected to the Internet. However, the uncertainty of NTP path delay measurements is typically multiple milliseconds due to routing changes and varying amounts of network traffic [10]. Because the path delay measurements of shortwave and Internet time signals have such large uncertainties, it is obvious that neither medium can support a 1 μs accuracy requirement.

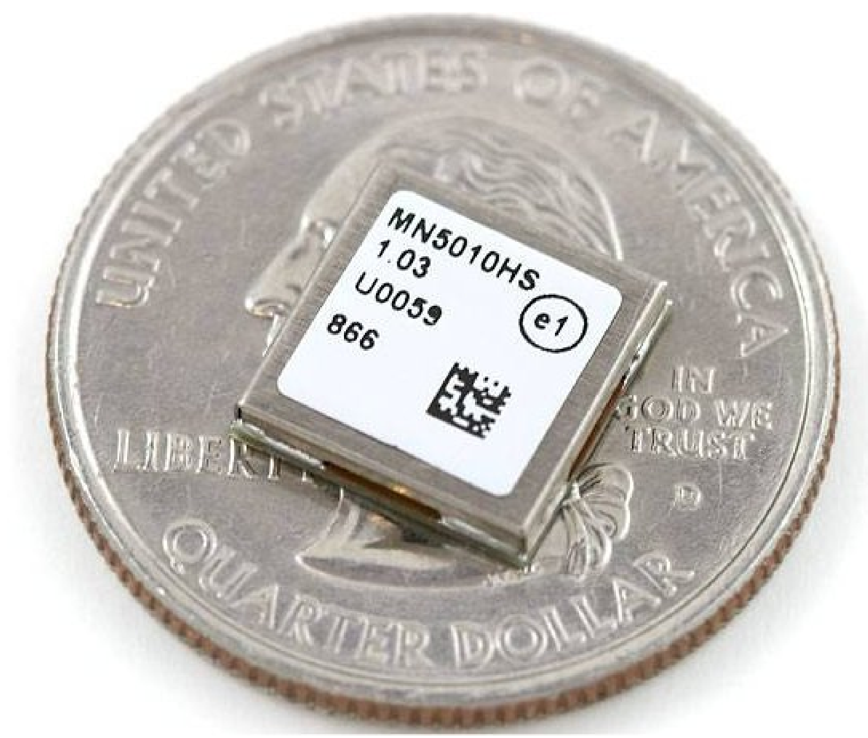

Fig. 2. A GPS receiver module (courtesy of Micro Modular Technologies).

In contrast, GPS clocks can easily provide sub-microsecond accuracy. A positioning, navigation, and timing (PNT) service, GPS includes as many as 32 satellites that orbit the earth at a height of 20,200 km. Each satellite carries atomic clocks that are steered from ground stations to agree with UTC as kept by the United States Naval Observatory (USNO). GPS signals are transmitted on several frequencies, but most clocks only receive the L1 carrier at 1575.42 MHz. Due to large investments in research and development, the receiver modules for GPS clocks are inexpensive and small enough to embed in just about any type of electronic device (Fig. 2).

GPS is a trusted time reference because its signals originate from atomic clocks controlled by the USNO, and because time accuracy is required in order for GPS to function as a positioning and navigation system. To illustrate this, consider that the maximum acceptable contribution from the satellite clocks to the positioning uncertainty is about 1 m, and that the satellite clocks can receive corrections from ground stations only once or twice per day. Because light travels at a speed of about 3×10^8 m/s, the 1 m requirement means that the satellite clocks need to stay accurate to within about 3.3 ns for periods of up to one day.

GPS has several advantages that allow the path delay between the reference and remote clocks (Fig. 1) to be measured very accurately. Because the time signals originate from the sky, there is an unobstructed path between the reference and remote clocks, which is not the case for clocks that broadcast time signals from terrestrial radio stations or through networks. This eliminates most significant variations in path delay. In addition, because GPS is a navigation system, the position of both the transmitter and receiver is known. The satellites transmit their position data, and the receivers determine their position by making a series of range measurements with multiple satellites. A free space calculation of the distance between the receiver and transmitter (using the speed of light as a constant), along with other corrections for relativistic effects and propagation delays, reduces the uncertainty of the path delay measurement to nanoseconds [11, 12, 13].

Table 1 summarizes the factors that limit the accuracy of a GPS clock. The two largest sources of uncertainty are often uncompensated hardware delays (mainly caused by the delay through the antenna cable), and antenna coordinate errors. The antenna cable delay is often ignored, but the delay through a RG-58 coaxial cable is only about 0.005 µs per meter. Even if a 50 m antenna cable is used, which is unlikely, only 0.25 µs of uncertainty would be introduced. GPS clocks generally survey their own position, and antenna coordinate errors add uncertainty. The estimates of latitude and longitude estimates are usually accurate to within 1 m, but the altitude estimate of an L1 band receiver can be in error by more than 10 m, in some cases introducing uncertainties as large as 0.05 µs. Other uncertainties, such as the additional delays incurred as the signals pass through the ionosphere and troposphere, are reduced by real-time corrections that the receiver applies based on propagation models.

Table 1. Time uncertainties of an uncalibrated GPS clock with respect to UTC.

Source of uncertainty	**Uncertainty in microseconds**	
	Best Case	Worst Case
Uncompensated hardware delays (receiver, antenna, and antenna cable)	0.005	0.250
Antenna coordinate errors (primarily altitude)	0.001	0.050
Multipath reflections (depends upon antenna type and antenna placement)	0.002	0.010
Signal delays through ionosphere (corrections applied by receiver)	0.002	0.020
Signal delays through troposphere (corrections applied by receiver)	0.002	0.020
Receiver delay changes due to temperature and environment	0.002	0.010

If we consider the uncertainties listed in Table 1 to be "worst case" and assume that they are uncorrelated and should be added together (a conservative assumption), an uncalibrated GPS clock should still be accurate to better than 0.4 µs with respect to UTC. In many cases, uncalibrated GPS clocks are within 0.1 µs of UTC. Because of their inherent accuracy without calibration, GPS clocks are often exclusively relied upon to support critical infrastructure systems. The following sections describe two of those systems; mobile phone networks and the electric power grid.

Why Mobile Phones Need Microsecond Accuracy

Code division multiple access (CDMA) mobile phone networks, such as those operated by Verizon, Sprint Nextel, U. S. Cellular, and others, rely heavily on GPS clocks. Base station clocks require 3 µs accuracy, and base stations that support multiple simultaneous CDMA channels require 1 µs accuracy [14]. To meet these requirements, CDMA system time is nearly always obtained from GPS clocks, and it is important to realize that CDMA mobile phone networks were designed based on GPS capability. The telecommunications industry maintains a very large number of GPS clocks. The exact number is unknown, but the CTIA (formerly an acronym for the Cellular Telephone Industries Association) estimates that over 283,000 mobile phone base stations were located in the United States at the end of 2011 [15], and if you look closely at a mobile phone base station, a GPS antenna can nearly always be found. Figure 3 shows a GPS antenna mounted above mobile phone antennas on a traffic light pole.

Fig. 3. GPS antenna (top of pole) deployed for mobile phone network.

CDMA base stations identify themselves via a time offset, and GPS clocks provide a common time reference that allows a nearly seamless handover of a mobile phone from one base station to another. The base stations operate in the same RF channel and are identified by a spread spectrum code. Each base station offsets the start of the code by a different time interval with respect to their common time reference.

As the time difference between base stations approaches 10 μs, the ability to support handovers begins to fail and the carrier-to-noise ratio of the connections will degrade. If the time difference exceeds 10 μs, base stations will eventually "collide" and mobile phone coverage is lost in the surrounding area.

Why the Power Grid Needs Microsecond Accuracy

The electric power grid is constantly expanding to meet the demands of consumers, and many transmission lines have been pushed to near their operating limits. It is now necessary to control the power grid in real-time, so that wide-scale cascading outages can be prevented. Today's "Smart Grid" (Fig. 4) requires the synchronization of phasor measurements made at power substations so that the state of the power system can be monitored in real time. Synchronized phasors, or synchrophasors, are referenced to an absolute point in time by using UTC as a common time reference. The devices that perform the synchrophasor measurements are known as phasor measurement units (PMUs). A PMU measures positive sequence voltages and currents at power system substations, and stamps each measurement with time obtained from a GPS clock. The measurements are then sent through a network to a central site, where the time stamps are aligned, the measurements are processed, and real time decisions are made about power allocations within the grid.

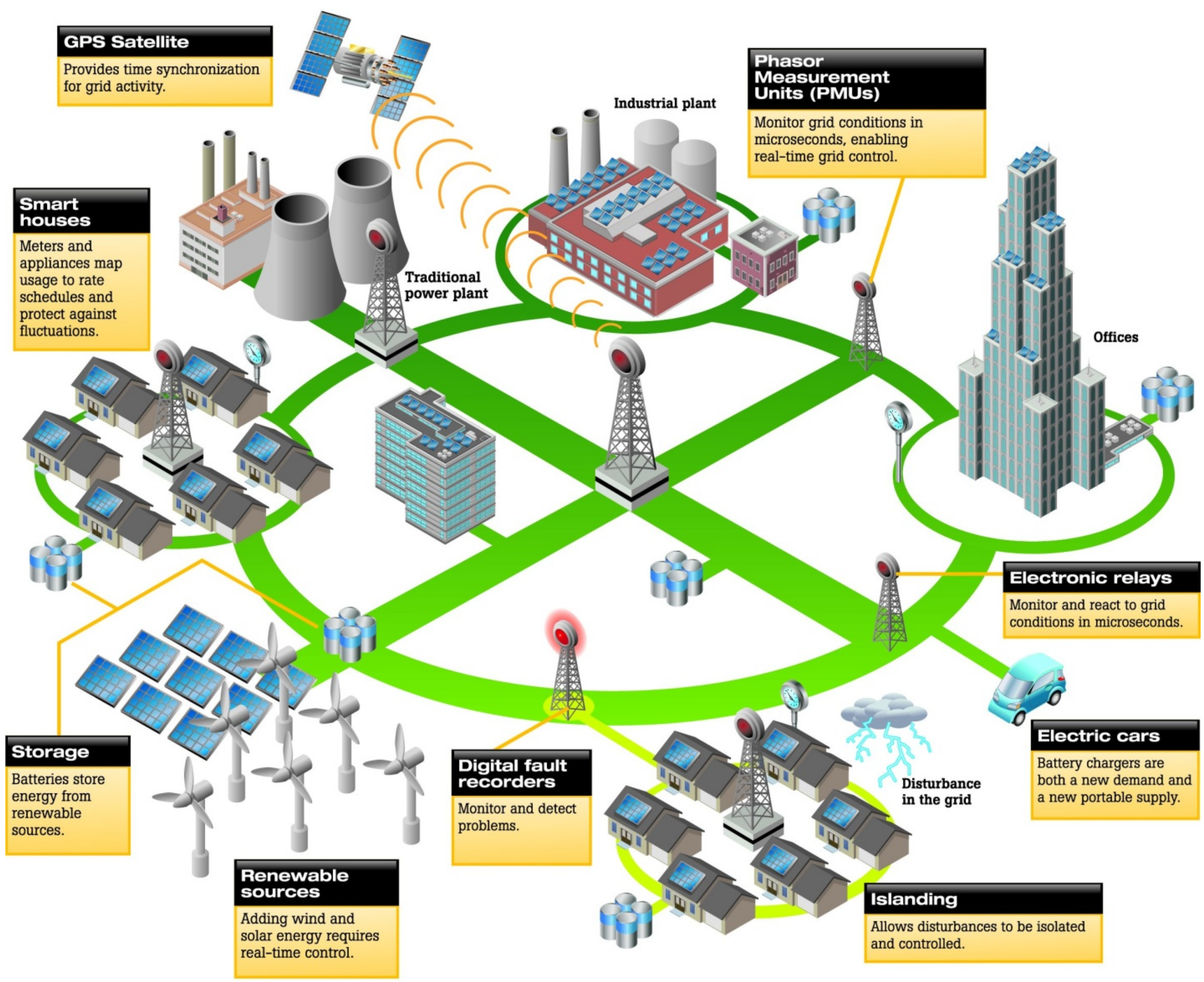

Fig. 4. The "Smart Grid" and its reliance on GPS time synchronization (courtesy of Fluke).

As was the case with CDMA, GPS clocks were an enabling technology for synchrophasor measurements. The first prototype PMU was assembled in 1988 with a GPS clock [16], and today commercial units are available from a number of vendors. The minimum PMU requirement for time synchronization is 26 μs, which corresponds to a phase error of 0.57 º at the 60 Hz AC line frequency [17]. The desired accuracy is 1 μs, which corresponds to a phase error of 0.022 °.

Why GPS is Vulnerable

GPS clocks are normally reliable, often providing uninterrupted service for many years without any attention. However, they can and do fail [18, 19]. The most likely cause of failure is probably RF interference, known as jamming, which can disable all GPS reception in a local area. GPS is susceptible to both intentional and accidental jamming due to the low power of the received signal. The GPS signal strength can be as low as –160 dBW when received on earth, equivalent to 10^{-16} W, and the loss of all PNT services in a given area can be caused by interfering signals that are only a few orders of magnitude more powerful. GPS jamming devices, although illegal, are relatively easy to build or buy. The handheld jamming device (sometimes referred to as a Personal Privacy Device, or PPD) shown in Fig. 5 is advertised as being able to block all GPS and mobile phone signals within a 20-meter radius, but the actual range of its disruption might be much larger. Higher power units are available that have a much larger radius.

Fig. 5. Handheld GPS jamming device.

When GPS signals are unavailable, GPS clocks must rely on their holdover capability to maintain synchronization. The holdover capability is provided by the clock's oscillator, which in most cases free runs in the absence of GPS (although some clocks store the oscillator's past performance data, and continue to adjust the oscillator during signal outages). A variety of oscillators are found inside of GPS clocks, ranging from tiny quartz crystal oscillators that cost just pennies when purchased in large quantities, to rubidium atomic oscillators that can cost several thousand dollars or more. Due to the differences in oscillator quality and other design factors, the length of time that a clock can continue to maintain critical infrastructure requirements without GPS is almost entirely device dependent. Some industrial grade GPS clocks will be out of tolerance in less than five seconds, and most will be out of tolerance in less than one hour. More expensive GPS clocks work much better, especially in temperature controlled environments, but even the best available clocks are unlikely to maintain microsecond accuracy for more than 10 days (an average frequency offset of 1×10^{-12}) without GPS reception.

Possible Backup Strategies for GPS Clocks

No currently available timing system has demonstrated the ability to meet the 1 μs accuracy requirement at thousands of geographically dispersed locations without relying on GPS. This has caused great concern about the need for a backup timing system [20, 21], and a number of backup strategies have been explored as described in the following sections.

Other Global Navigation Satellite Systems (GNSS)

GPS was the original global navigation satellite system (GNSS), but several other systems now exist, or are in the process of being built, by entities outside of the United States. These include GLONASS (Russia), Galileo (Europe), and COMPASS (China) [22]. As of May 2012, GLONASS is fully operational, and the satellite constellations of Galileo and COMPASS have been partially launched. Receivers capable of simultaneously tracking all of these GNSS signals are already commercially available.

There are political and technical arguments against relying on another GNSS system as a backup timing source for GPS in the United States. The political argument is simply that it is not a good idea, from the viewpoint of national security, to allow critical infrastructure systems to obtain their reference time from systems controlled from outside of the United States. The technical argument is simply that the GNSSs operate on similar frequencies (Table 2), and that intentional jamming could simultaneously disable all of them [23].

Table 2. GNSS carrier frequencies (in megahertz).

GPS	GLONASS	Galileo	COMPASS
L1 1575.42	L1 1602.00	E1 1575.42	B1 1575.42
L2 1227.60	L2 1246.00	E5 1191.795	B2 1191.795
L5 1176.45		E5A 1176.45	B3 1268.52
		E5B 1207.14	
		E6 1278.75	

Low Frequency Navigation Systems

In 2010, the U. S. government elected to shut down the LORAN-C radio navigation system, which had operated in various forms since World War II, transmitting signals at 100 kHz [24]. Prior to the shutdown, many of the LORAN stations had been modernized to support a new form of phase modulation that improved their navigation and timing accuracy. This enhanced system, called eLoran, easily provided sub-microsecond accuracy, and its high power, low frequency signals were extremely difficult to jam.

Ironically, it had been recommended by an independent assessment team as the primary backup timing system to GPS just one year prior to its shutdown [25].

Due to a lack of alternatives, eLoran may still be revived as the backup timing source to GPS [26]. The U. S. Coast Guard, which formerly operated LORAN-C, has recently entered into a cooperative research and development agreement with Ursanav, Inc., to examine developing a backup system for GPS based on eLoran technology. At this writing (May 2012), experimental signals are being broadcast from the former LORAN support unit site in Wildwood, New Jersey, and Ursanav has acquired the intellectual property rights from several companies that formerly manufactured LORAN receivers.

Precision Time Protocol (IEEE-1588) and eSync

Network timing signals are often mentioned as an alternative to GPS time, and sub-nanosecond accuracy has been demonstrated over fiber optic networks [27]. Commercially-available timing systems based on the Precision Time Protocol (PTP) [28] and Synchronous Ethernet (SyncE) [29] have demonstrated the ability to provide sub-microsecond accuracy in a local area network (LAN). However, when implemented on wide area network (WAN) such as the Internet, where the path delays are highly variable and uncontrolled, their accuracy is often similar to NTP [10] and reduced to milliseconds.

Network timing systems vary in complexity, but all are based on some variation of two-way time transfer (Fig. 6). The round trip delay between the clock is measured, and the path delay, d, from the reference to the remote clock is assumed to be half of the round trip delay between the clocks, thus $d = (d_{ab} + d_{ba}) / 2$. The reference clock either advances the time to compensate for path delay, or the path delay is added as a correction when synchronizing the remote clock. The path delay assumption is true if the path is symmetric, and $d_{ab} = d_{ba}$. However, the path is usually asymmetric ($d_{ab} \neq d_{ba}$) and a synchronization error is introduced [30]. In a WAN, this synchronization error is generally far too large to support 1 μs accuracy.

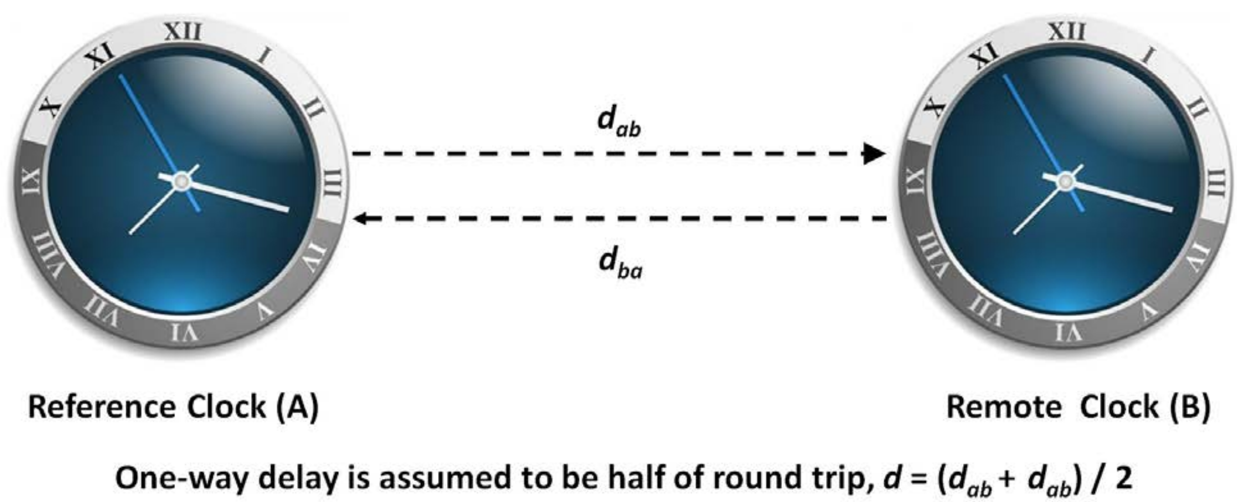

Fig. 6. A two-way time transfer system.

A network solution that meets critical infrastructure timing requirements would either require a WAN based on fiber optics that is dedicated to timing (or at least tightly controlled), or deploying large numbers of reference clocks to supply time over short distances to LANs. The first solution is cost prohibitive. The second solution brings us back to square one – where would the reference clocks come from if GPS clocks could not be used? Unlike GNSS systems, which provide the reference clock and the time transfer system, systems such as PTP and SyncE provide only the time transfer system, and must be referenced to external clocks.

Chip Scale Atomic Clocks

Another backup strategy that is sometimes suggested is simply to deploy many thousands of atomic clocks. Of course, the architects of industrial timing systems lack the budget to do so, which explains why costly cesium clocks (~ $70,000 USD) are rarely found within telecommunication networks and power grids, and why most GPS clocks contain quartz, rather than rubidium oscillators. However, the recent availability of the chip scale atomic clock (CSAC) makes the widespread deployment of atomic clocks more feasible [31]. The CSAC (Fig. 7) is a fraction of the size of other atomic clocks, with dimensions of approximately 40 × 35 × 11 mm and a weight of less than 35 g. It is also more stable than a quartz oscillator, maintaining frequency stability of a few parts in 10^{12} for several hours. CSACs are a new product, first appearing commercially in 2011. As the technology matures, their price could drop to about $100 per unit.

Fig. 7. A chip scale atomic clock (courtesy of Symmetricom).

It is important to remember, however, that like all atomic clocks, the CSAC is simply a frequency standard. Unlike a GPS clock, it cannot recover time by itself, and can only serve as a reference clock after being synchronized to a UTC source. It can, however, lead to the development of low cost GPS clocks with improved holdover capability.

Common-View Disciplined Clocks

A possible solution to the microsecond accuracy problem involves synchronizing multiple clocks to a non-GPS reference clock through the use of common-view measurements. The common-view measurement technique is an established way to compare clocks located at different sites. The time difference between two clocks is measured by simultaneously comparing both clocks to a signal from an independent transmitter that can be received at both sites. The common-view signal (CVS) is simultaneously received at sites *A* and *B*, where it is compared to the local clocks. Thus, the measurement at site *A* produces the time difference *Clock A – CVS*, and the measurement at site *B* produces *Clock B – CVS*. When the two measurements are subtracted from each other, the result is *Clock A – Clock B.*

The common-view technique was practiced long before the first GPS satellites were launched [32], but GPS has typically provided the CVS source for the past several decades [33]. Note, however, that the

CVS does not have to originate from an accurate time source, it is simply a vehicle used to transfer time from the reference to the remote clock. It is, of course, necessary for the measurement systems at both sites to be calibrated, so that their path delays are equivalent. This allows the CVS errors to "cancel" and for the measurement result to show only the difference between the two clocks. Common-view GPS comparisons produce very good results, with a typical measurement uncertainty of about 0.01 μs.

Common-view measurements can also be used to control clocks [34]. To make this happen, the measurements must be rapidly processed so that the time difference between the reference and remote clock is continuously known. This time difference is sent as a correction to the remote clock to make it agree with the reference clock (Fig. 8). The "measure and correct" process is continuously repeated to keep a common-view disciplined clock (CVDC) locked to its reference clock. The data server in Fig. 8 can potentially support a large number of CVDCs, because only a small amount of data needs to be processed during each transaction.

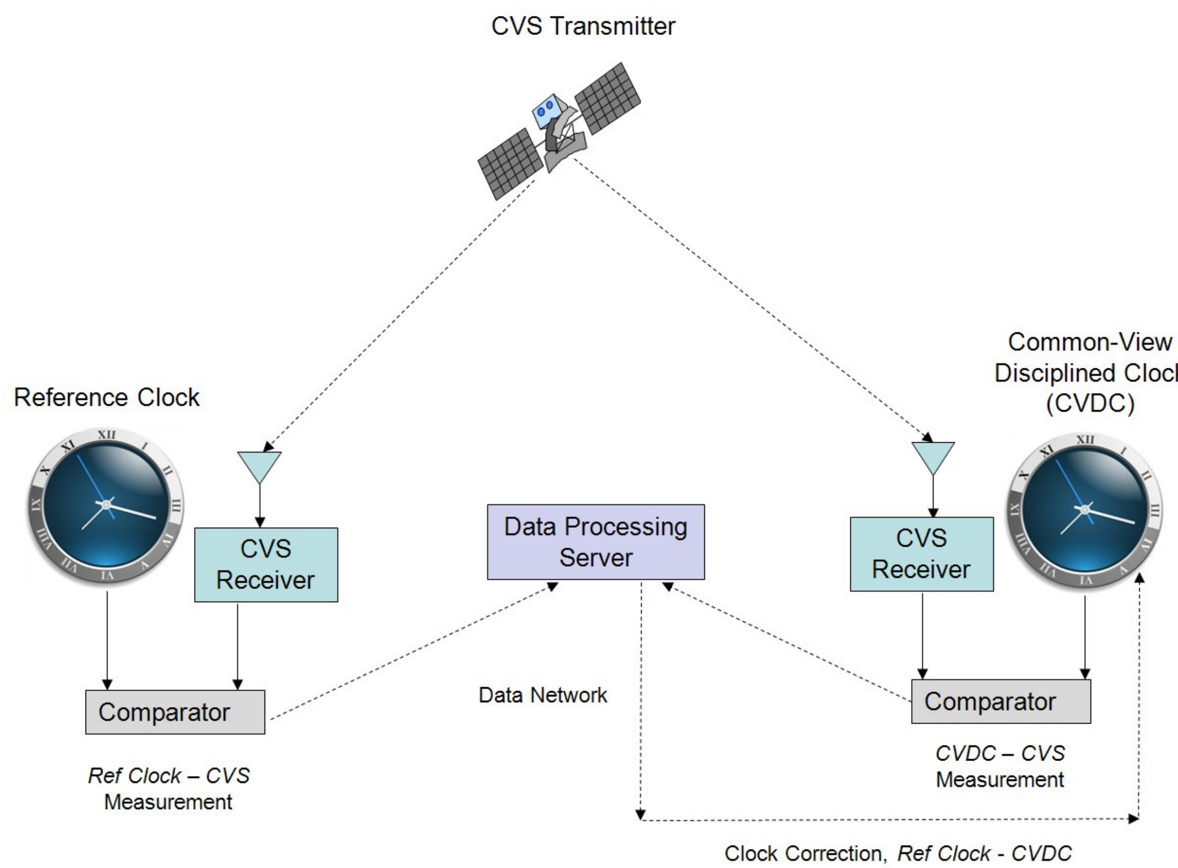

Fig. 8. A common-view disciplined clock (CVDC) system.

Systems similar to Fig. 8 exist in the United States [35] and Japan [36], and routinely provide sub-microsecond accuracy. However, these systems use GPS as their CVS source, and thus depend on GPS availability. With additional research and development, however, the CVDC concept could be extended to develop a "fail-safe" clock that could work without GPS.

To illustrate how a "fail-safe" clock could work, consider that a CVDC relies on three main components: (1) A reference clock, (2) a common-view signal, and (3) a data network. Each component could have one or more backups, and the system could be designed to automatically switch to a backup component whenever necessary. For example, if a reference clock at the National Institute of Standards and Technology (NIST) becomes unavailable, a CVDC could automatically switch to a reference located at USNO. In theory, any clock that makes common-view measurements available through the data network could be chosen as the reference.

Other GNSS satellites could be used as backup CVS sources. We described earlier how systems such as GLONASS and Galileo, are not generally accepted, for national security reasons, as the time reference for critical infrastructure systems within the United States. However, they might be acceptable as a backup CVS source, because they would not be supplying the reference time, but instead only used to "relay" the reference time to another location. Many GPS receivers and antennas are now compatible with other GNSS systems, so the additional hardware cost required for a backup CVS source might be small, although the concerns expressed earlier about all GNSS signals being simultaneously jammed would still apply.

Another possibility would be to use signals from geostationary communication satellites as the CVS source. The use of communication satellites would require more effort, because the position of the satellite, the reference clock, and the remote clock would need to be known in order to accurately measure path delay. However, these problems are not insurmountable. The satellite position could be obtained either from its broadcast or through calculations involving orbital elements. The position of each remote clock would only need to be determined once, and would already be known if GPS were the primary CVS source.

Providing multiple data networks to remote clocks should be possible. The public Internet can be utilized, along with wired and wireless telecommunication networks. The path delay through the data network is not important, because timing signals would not be sent through the network, only clock corrections. Multiple servers would, of course, be needed for redundancy.

By automatically switching to a backup component whenever a primary component fails, a CVDC could potentially meet critical infrastructure timing requirements even in extreme scenarios where the reference clock, GPS, and the data network are all unavailable. Table 3 lists some possible primary and backup components for a "fail-safe" CVDC.

Table 3. Primary and backup components for "fail-safe" CVDC.

Components	**Reference Clock**	**Common-view signal**	**Data Network**
Primary Components	UTC(NIST) or UTC(USNO)	GPS	Public Internet
Backup Components	Other national or private time scales that are synchronized to UTC	Other GNSS systems (GLONASS, Galileo, COMPASS) Geostationary communications satellite	Private telecommunication network (wired or wireless)

Summary and Conclusion

Critical infrastructure timing systems depend heavily upon GPS, simply because microsecond accuracy is easy to achieve with GPS and difficult to achieve without it. This paper has discussed how GPS clocks meet critical infrastructure timing requirements, why they are vulnerable, and some possible backup strategies. It seems clear that achieving microsecond accuracy at thousands of geographically dispersed locations without relying on GPS clocks is a very challenging problem. It seems equally clear that solving this problem is in the best interest of the United States.

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